Prospects for Laser Cooling of Semiconductors

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Abstract: Anti-Stokes fluorescence cooling of semiconductors is theoretically investigated. Calculations show that semiconductor-based optical refrigerators may operate below 10 K with efficiencies comparable to those of small mechanical cryo-coolers.

Following the first observation of optical refrigeration in a solid (ytterbium-doped glass) in 1995 [1], anti-Stokes fluorescence cooling has been reported in a variety of rare-earth doped solids as well as organic dyes. There have been theoretical and experimental investigations of anti-Stokes cooling of semiconductors, although no net cooling has been demonstrated yet due to radiation trapping [2–5]. Once this issue is resolved, semiconductor structures may offer superior performance compared to rare-earth doped materials and provide a practical, all-solid-state and vibration-free cryo-cooler. Here, we address important issues pertaining to optical refrigeration in semiconductors, including the cooling efficiency and lowest achievable temperatures. Specifically, we study the effects of many-body and Coulomb interactions, band-filling, and electron-phonon dynamics.

Fig. 1 illustrates the optical-refrigeration mechanism for a direct-bandgap semiconductor such as GaAs in a two-band model. The pump light is tuned just below the edge of the bandgap (i.e. in the Urbach tail) and excites 'cold' free carriers. On a timescale of the electron-phonon interaction, the free electrons and holes absorb lattice heat via phonon scattering. These 'warm' excited carriers recombine by emitting higher energy photons on a timescale of the flourescence lifetime, thereby cooling the semiconductor.

For uniform illumination, the steady-state electron-hole density (N) is given by

$$0 = \frac{\alpha(\nu, N)}{h\nu} I - AN - BN^2 - CN^3 \tag{1}$$

where α is the absorption coefficient and I is the laser intensity. A, B, and C are the nonradiative, radiative, and Auger recombination coefficients, respectively. Assuming carrier thermalization with the lattice occurs on a timescale much faster than any of the decay processes and an efficient out-coupling of the luminescence, the cooling power density is:

$$P_{cool} = BN^2(h\nu_f - h\nu) - ANh\nu - CN^3 h\nu - \sigma_{fc} NI \tag{2}$$

where $h\nu_f$ is the mean fluorescence (luminescence) photon energy and $\sigma_{fc}(T)$ is the free-carrier absorption cross-section. All coefficients in Eqs. (1)–(2) are temperature-dependent. The effects of Coulomb interactions (excitons and screening) as well as band-blocking (saturation) are included in the interband absorption coefficient α by using the analytical theory of Banyai and Koch [6]. We study bulk GaAs and investigate its performance at low temperatures (down to 10 K) at various carrier densities, which is controlled by the optical intensity.

Fig. 2 shows the calculated absorption coefficient, luminescence spectra, and cooling efficiency (defined as $P_{cool}/P_{absorbed}$, where negative values indicate heating) at T = 10, 70 and 150 K. The carrier concentrations are chosen to be slightly above the absorption saturation density for each temperature. At T = 10 K and 70 K, the n = 1 exciton plays a key role in the cooling process. The n = 2 and higher bound excitons are screened by the e-h plasma. The efficiency increases from ~ 0.1 % at T = 10 K to more than 1.5% at T = 150 K. These efficiencies are just slightly below those of small mechanical coolers. Our calculations indicate that cooling can be achieved at lower temperatures (e.g. 4 K) but only with small carrier concentrations ($<10^{12}$ cm^{-3}) corresponding to a very low cooling power density. There are some fundamental considerations, however, that limit this analysis from making accurate predictions at temperatures below 10 K. A more sophisticated treatment of laser cooling in semiconductors is in progress and will include: i) a more rigorous model for absorption and luminescence that includes exciton-exciton screening, the exciton-photon polariton, and hot exciton effects, ii) thermalization dynamics of the excitons, which becomes considerably slower when the average thermal energy is less than the optical phonon energy, i.e. when $kT << \hbar\omega_{LO}$.

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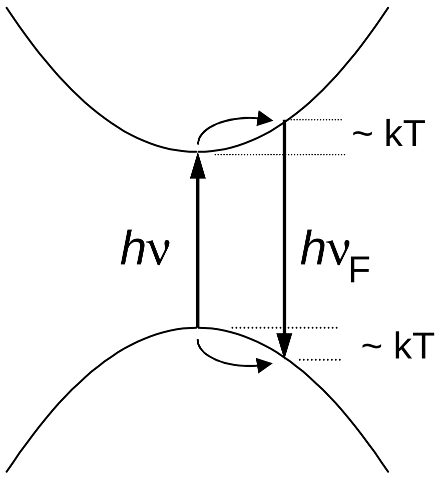

Fig.1 Cooling cycle in laser refrigeration of a semiconductor: a laser photon with energy $h\nu$ is absorbed followed by blue-shifted luminescence at $h\nu_F$.

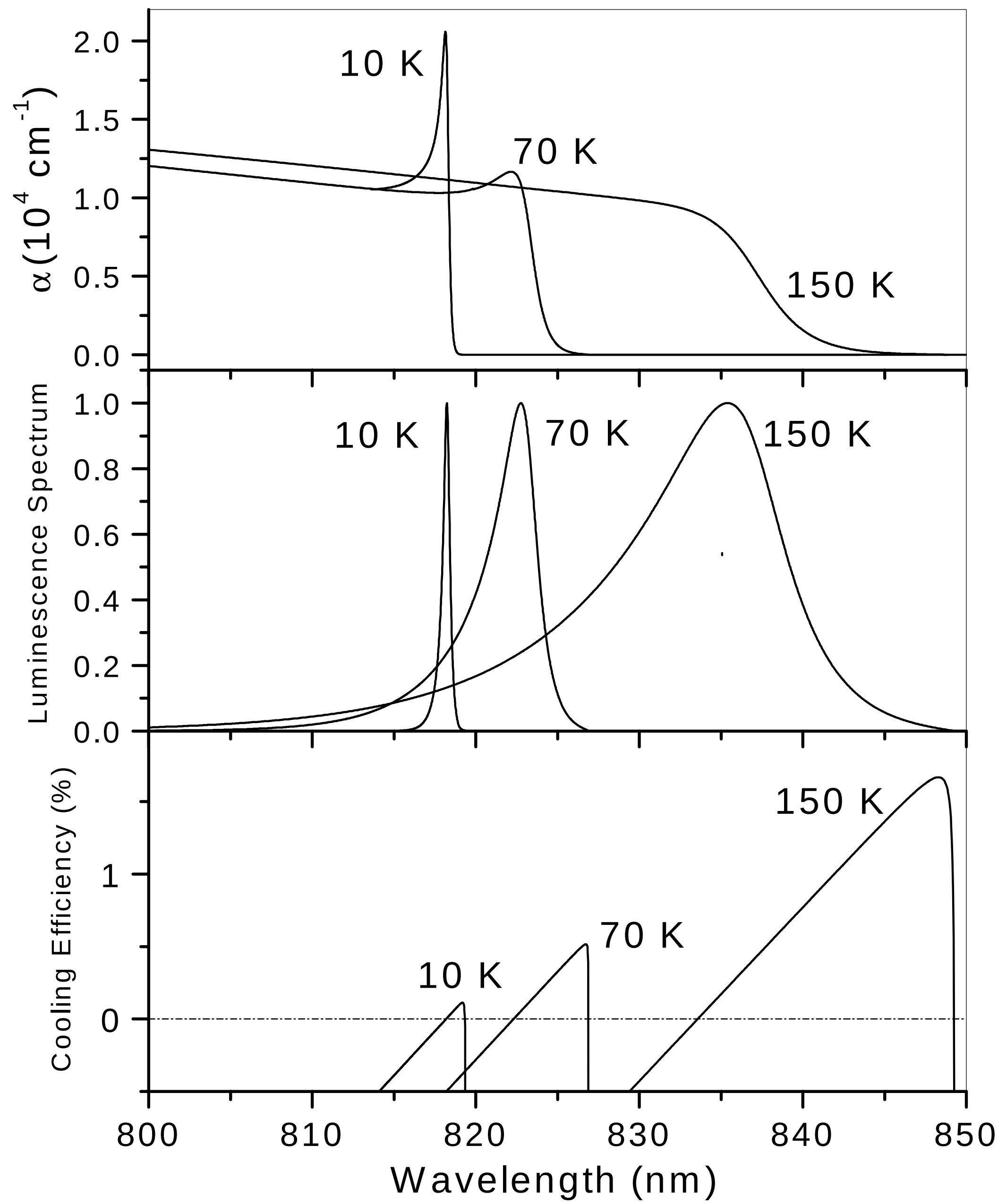

Fig.2 Calculated absorption spectra (top), luminescence (middle), and cooling efficiency (bottom) in GaAs for temperatures and densities corresponding to the threshold for absorption saturation: i) $T = 10$ K, $N = 3\times10^{15}\ cm^{-3}$, ii) $T = 70$ K, $N = 3\times10^{16}\ cm^{-3}$, and iii) $T = 150$ K, $N = 1\times10^{17}\ cm^{-3}$. Positive efficiency indicates cooling.